

A comprehensive review of adult scoliosis: Advances in pathogenesis, diagnosis, and management strategies

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ABSTRACT

Adult scoliosis is a three-dimensional complex deformity of the spine where the Cobb angle is over 10°. Understanding the severity of the deformity, etiology, and planning management strategies is assisted by classification systems with their emphasis on sagittal balance modifiers such as sagittal vertical axis and pelvic incidence. According to epidemiological studies, this deformity is getting more prevalent among the elderly due to progressive spinal degeneration. Adult scoliosis has a wide range of manifestations and symptoms ranging from neurogenic claudication and back pain to psychosocial effects and postural imbalance. For the overall diagnostic evaluation, actions such history-taking, physical examination, and assessing the individual's quality of life play an essential role. However, the precise diagnosis of this deformity can be significantly assisted by radiographic methods making use of sagittal modifiers and the Cobb angle, and advanced imaging systems such as computed tomography and magnetic resonance imaging. Practices such as bracing, physical therapy, and pharmacological interventions are considered conservative treatments, while surgical options are preferred for severe deformities, which include spinal fusion and osteotomies.

Keywords: Adult scoliosis, adult spinal deformity, conservative treatment, degenerative scoliosis.

Scoliosis is a three-dimensional deformity of the spine, which is displayed by a Cobb angle over 10°, and for its assessment, measurements of coronal plane deviation is required, which is achieved through making use of standing radiographs.^[1,2] This condition has been classified into a wide range of types, each of which manifest themselves in different stages of life. Aebi^[3] presented a classification for adult scoliosis and divided it into three primary categories, while Berven and Lowe^[4] introduced two additional types, expanding on Aebi's framework. These two types were posttraumatic and postsurgical scoliosis.

The two primary forms of scoliosis are adult idiopathic scoliosis (AdIS) and adult degenerative (de novo) scoliosis (ADS). Adult idiopathic scoliosis has its origin in adolescent idiopathic scoliosis and persists into adulthood. Contrarily,

ADS develops when the structural elements of the spine progressively deteriorate, which causes misalignment and structural deformity.^[5] Adult idiopathic scoliosis and ADS present with divergent clinical profiles and management strategies. One of the main characteristics of AdIS is a persistent long-standing curve since adolescence, having the potential to progressively worsen and cause pain and functional limitations, which are addressed by supervision and targeted interventions.^[6] However, ADS is mainly considered to be associated with age-related degenerative processes, and its most common manifestations are neurogenic claudication, postural instability, and chronic back pain. For the most part, this condition requires a multidisciplinary approach that utilizes conservative treatments, but in advanced cases with elevated symptoms, surgical interventions are necessary to correct the alignment and alleviate symptoms.^[7]

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Classification

Classifications of scoliosis have been developed to facilitate a comprehensive understanding of the etiology, clinical features, and radiologic findings of the condition, as well as to inform management strategies.

Aebi classification

Aebi's^[3] classification of adult scoliosis divides adult scoliosis into three main categories, focusing on etiologic factors (Table 1). The classification system is appropriate for general use and provides a fundamental framework. However, it has certain limitations. It cannot offer specific information regarding clinical severity, sagittal balance, surgical indications, or treatment planning.^[8]

The Scoliosis Research Society-Schwab classification system, developed by the Scoliosis Research Society in collaboration with Schwab, provides a comprehensive framework for evaluating adult spinal deformity.^[9] By integrating radiographic parameters such as coronal curve magnitude (Cobb angle; Table 2), sagittal vertical axis (SVA), and pelvic

parameters [pelvic tilt (PT), pelvic incidence (PI), and sacral slope (SS)], it assesses spinal deformity severity and clinical impact (Figure 1; Table 3). Sagittal modifiers such as PI-lumbar lordosis, SVA, and PT offer detailed insights into alignment, aiding in surgical planning and evaluating the impact on function and quality of life.^[10,11] One limitation of Schwab classification system was that the focus was primarily on radiographic parameters. Less emphasis was placed on neurological or pain-related factors

Scoliosis Research Society-Schwab Classification of Thoracolumbar Scoliosis

The Lenke classification is a comprehensive system for categorizing AdIS based on the total curve pattern and radiographic parameters. It assesses three main aspects: coronal curve types (six curve patterns), lumbar modifiers (relative to the central sacral vertical line), and sagittal thoracic profiles (hypokyphosis, normal, or hyperkyphosis). The comprehensive nature of this classification system enables a three-dimensional evaluation of spinal deformities, thereby guiding surgical planning and standardizing treatment strategies.^[12] Building on

TABLE 1
Classification of adult scoliosis

Type	Description	Key features	Associated conditions
Type 1 - Primary degenerative (De Novo) scoliosis	Asymmetric degeneration of intervertebral discs and facet joints; often termed discogenic curvature.	- Affects lumbar or thoracolumbar regions (L3-L4, L2-L3, L1-L2). - Rotational translation of apical vertebra. - Sagittal malalignment. - Associated with spondylosis, disc bulging, osteophytes, and spinal stenosis.	Spondylosis, disc degeneration, facet arthropathy, spinal stenosis.
Type 2 - Progressive idiopathic scoliosis	Continuation of adolescent idiopathic scoliosis with progression due to mechanical or degenerative changes.	- Predominance of flatback syndrome. - Loss of lumbar lordosis or development of kyphosis. - Frequently involves lumbar or thoracolumbar spinal stenosis.	Adolescent idiopathic scoliosis with adult progression.
Type 3A - Secondary adult scoliosis	Results from adjacent idiopathic, neuromuscular, or congenital curves, leg length discrepancies, or prior spinal surgery.	- Often linked to conditions like neuromuscular disorders. - May result from leg length discrepancies or postsurgical changes.	Parkinson's disease, Marfan syndrome, syringomyelia, spinal surgery sequelae.
Type 3B - Bone weakening disorders	Caused by bone weakening disorders leading to spinal deformities.	- Vertebral fractures causing asymmetrical spinal deformities. - Exacerbation of pre-existing scoliosis or kyphosis.	Osteoporosis, metabolic bone disorders.

TABLE 2 Scoliosis Research Society-Schwab classification of thoracolumbar scoliosis	
Coronal curve types	Description
T	Thoracic only, with lumbar curve <30°
L	Thoracolumbar/lumbar only, with thoracic curve <30°
D	Double curve, with at least one thoracic and one thoracolumbar/lumbar curve, both >30°
N	No major coronal deformity; all coronal curves <30°

this foundation, in 2021, a radiological classification system proposed by Lin et al.^[13] expanded the Lenke model to include parameters tailored to adult spinal deformities and other complex scoliosis cases. This expanded version integrates sagittal balance, spinopelvic parameters, and compensatory mechanisms, enhancing its applicability in a broader range of spinal conditions.

Epidemiology and Pathogenesis

Adult degenerative scoliosis typically manifests with a balanced sex distribution, with onset occurring around the age of 50 and a mean clinical presentation age of approximately 70 years. Epidemiological studies indicate that the prevalence of adult scoliosis varies widely, ranging from 2 to 32% in the general population. It ranges from 8% in adults aged 25 to 74 years and rises to 68% among individuals aged 50 years or older.^[14-17] It is

noteworthy that the prevalence of scoliosis exhibits an inverse correlation with the magnitude of the curve, as a significant proportion of cases comprise asymptomatic, minor curvatures.^[18,19]

The etiology of ADS, particularly scoliosis, is a multifaceted process involving mechanical, biological, and environmental factors.^[3] It begins with asymmetric forces acting on the vertebral structures, leading to progressive changes in disc integrity, vertebral morphology, and spinal alignment.^[2,20-22] Over time, these factors contribute to structural imbalances in both the coronal and sagittal planes, exacerbating the deformity through a vicious cycle of mechanical loading and degenerative processes.^[23] The resultant spinal instability, postural changes, and associated symptoms, including back pain and neural compression, are the consequence of this interplay of elements. The sequence of events is visually summarized in Figure 2.

Curves with a magnitude less than 30° tend not to progress during adulthood. However, curves with a magnitude between 30° and 50° have a 70 to 80% risk of progression, while curves with a magnitude of 50° or more have nearly 100% risk of progression.^[24,25] Weight or hormonal changes during pregnancy, menopause, osteopenia or osteoporosis, and other factors may contribute to the potential for more rapid curve progression.^[26]

Clinical Presentation

Adult scoliosis is a multifaceted condition with symptoms influenced by deformity severity, progression, and etiology. While some patients remain asymptomatic due to mild deformities or compensatory mechanisms, others experience significant physical, functional, and psychosocial impairments.^[14,27,28]

Back Pain

Back pain, affecting up to 90% of patients, is the most common symptom.^[29] It results from muscle fatigue, degenerative changes, and mechanical

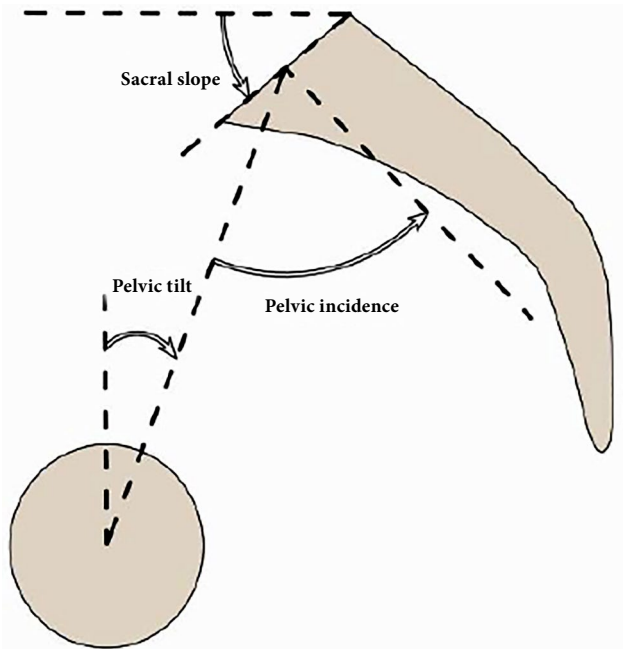


Figure 1. The schematic illustration demonstrates the three key pelvic parameters used in sagittal alignment analysis.

TABLE 3 Sagittal modifiers for Scoliosis Research Society-Schwab classification of thoracolumbar scoliosis		
Sagittal modifier	Grade	Description
Pelvic incidence (PI), -lumbar lordosis (LL)	0	Within 10°
	+	Moderate (10°-20°)
	++	Marked (>20°)
Sagittal vertical axis (SVA)	0	SVA <4 cm
	+	SVA 4-9.5 cm
	++	SVA >9.5 cm
Pelvic tilt (PT)	0	PT <20°
	+	PT 20-30°
	++	PT >30°

instability. Pain often localizes to the curve apex or concavity, involving paravertebral muscles and facet joints. Fatigue of overloaded muscles and loss of lumbar lordosis (flatback syndrome)^[30] exacerbate the discomfort, often relieved by lying down.

Neurogenic Claudication and Radiculopathy

Neurogenic claudication presents with leg pain, numbness, and weakness worsened by standing or walking and relieved by supported sitting. Central or foraminal stenosis, due to ligamentum flavum

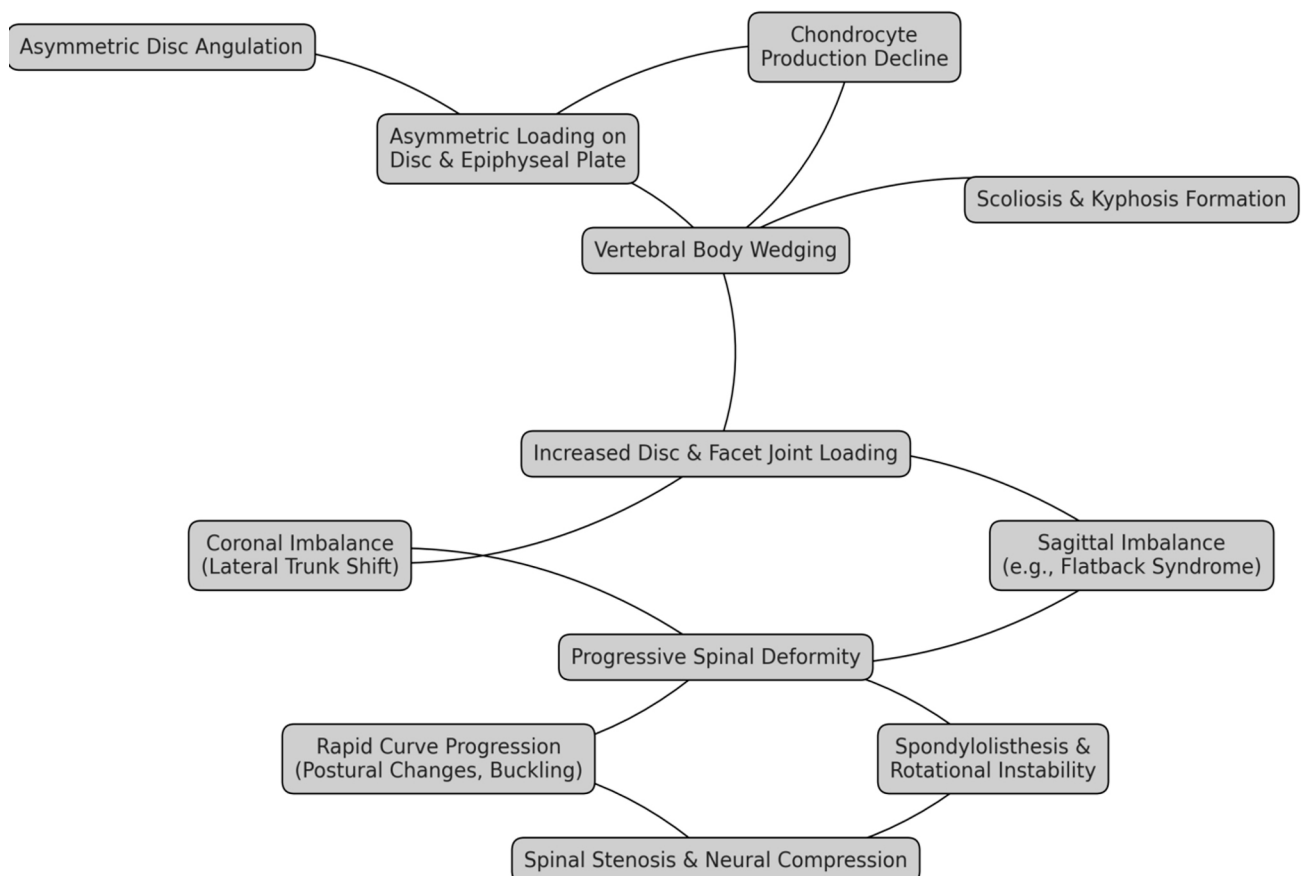


Figure 2. Pathogenesis of spinal deformity progression.

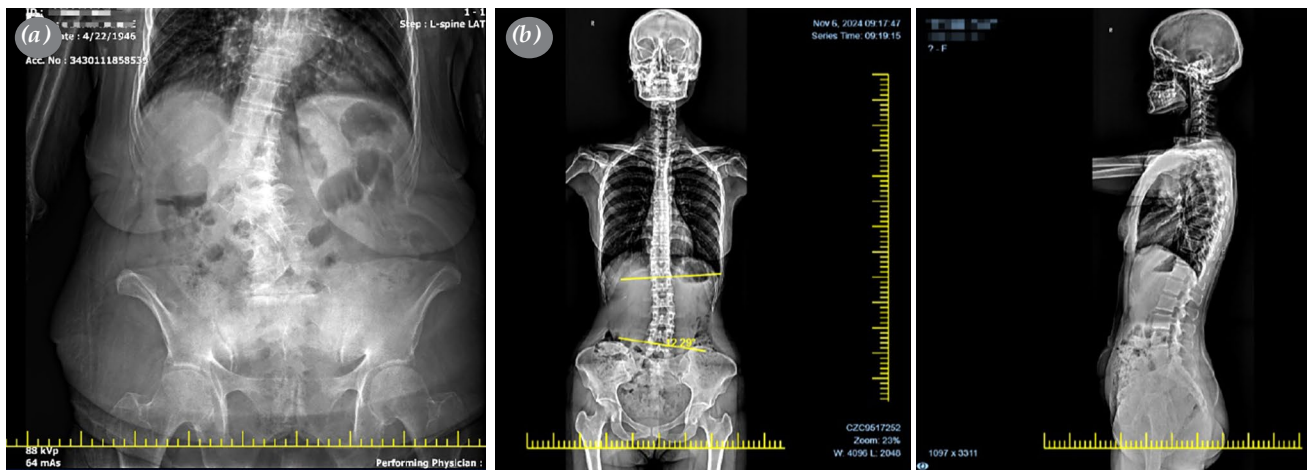


Figure 3. (a) An anteroposterior radiograph of the lumbar spine of a 78-year-old female patient, demonstrating scoliosis with degenerative changes, including intervertebral disc space narrowing, osteophyte formation, and pelvic asymmetry, typical of ADS. (b) An anteroposterior radiograph of the lumbar spine demonstrating scoliosis with Cobb angle measurements marked on the coronal plane. The most tilted vertebrae above and below the curve apex are identified, and their corresponding endplate lines are drawn to calculate the Cobb angle. This measurement provides a quantitative assessment of the severity of the scoliotic deformity. The lateral view of the same radiograph allows for evaluating sagittal balance parameters such as lumbar lordosis and thoracic kyphosis, contributing to the comprehensive analysis of spinal alignment.

hypertrophy, disc bulging, or facet degeneration, is a typical cause. Radiculopathy manifests as pain and weakness radiating to the lower extremities, driven by nerve root compression or traction, particularly on the concave and convex curve sides, respectively.^[3,12,20,30]

Postural Imbalance

Postural deformity, a hallmark of scoliosis, encompasses coronal imbalance with lateral trunk shifts and asymmetry in shoulder or pelvic alignment, and sagittal imbalance characterized by loss of lumbar lordosis and forward-leaning posture, leading to increased spinal load and functional limitations.^[3,12,30]

Curve Progression

Curve progression, driven by factors such as Cobb angles $>30^\circ$, lateral listhesis >6 mm, and vertebral collapse, amplifies axial and radicular pain, postural imbalance, and neurologic impairments. Rapid progression often necessitates surgical intervention to prevent further decline.^[31]

Psychosocial Concerns

Scoliosis significantly impacts self-image and mental health, with concerns about posture, curve progression, and physical appearance, potentially contributing to depressive symptoms and reduced quality of life.^[32]

Clinical Evaluation

In regards to screening scoliosis, it is important to pay attention to any unexpected height loss and presence of spinal deformities as these might be indicators of a worsening condition. Documenting the age of diagnosis and prior interventions and evaluating the curve over time allows a comprehensive assessment of progression risk. Patients frequently report alterations in posture and balance, which may be indicative of exacerbation of scoliosis, vertebral collapse, or disc failure.^[3] The characterization of pain is vast, including its location, intensity, and alleviating and aggravating factors. Radicular pain may indicate nerve root compression, whereas axial pain is mostly considered to be related to degenerative changes.^[2] A comprehensive review of the patient's medical history, including prior spine surgery, bone density scans, and hormonal changes related to menopause, is imperative.^[33] Scoliosis may have a genetic component, and therefore, family history is crucial for early diagnosis and treatment in at-risk individuals.^[3] Osteoporosis is a prevalent condition among patients with ADS, with a concomitant significant increase in the risk of vertebral fractures. These fractures have the potential to exacerbate spinal deformities, leading to accelerated curve progression and a decline in functional capacity.^[34,35] Within the context of ADS, the interpretation of imaging findings might get complicated, as the

degenerative changes can make images hard to interpret (Figure 3a).^[36] Conventional radiographic and bone density scans might be constrained by scoliosis-related artifacts, whereas advanced imaging techniques such as quantitative computed tomography and standing electro-optical system imaging provide three-dimensional, more precise, and weight-bearing assessments. Intergrading these advanced techniques enables precise diagnosis and facilitates correct and effective treatment for complex ADS cases.^[36,37]

Physical Examination

The physical examination provides an objective assessment of the severity and functional impact of the deformity. Examination of posture for asymmetry in the shoulders, scapulae, and trunk alignment helps to identify coronal and sagittal imbalances, including thoracic kyphosis or lumbar flatback.^[2,3,20] Adam's forward bend test is used

to detect rotational deformities, and scoliometer measurements are used to measure the angle of trunk rotation.^[32,38] Palpation is a key component of the examination, as it detects tenderness along the spine and sacroiliac joints, indicating the presence of localized arthritis or fractures. Postural and gait assessments evaluate coronal and sagittal balance, as well as gait patterns, to identify potential mechanical imbalances or neurological impairments. Measurement of leg length differences is also crucial, as it can detect inequalities that may exacerbate spinal loading and deformities.^[2,3,30]

Radiographic evaluations

Initial imaging typically includes standing posteroanterior (PA) and lateral views to provide comprehensive spinal imaging, with additional imaging performed when clinically indicated (Figure 3b).^[3,39] It is imperative that standing radiographs encompass the entire spine and the

TABLE 4
Nonsurgical management options for adult scoliosis

Management option	Description	Purpose
Physical therapy (PT)	Tailored exercises, including core strengthening, flexibility, and postural training. Physiotherapeutic scoliosis-specific exercises (PSSE), such as the Schroth method, are often employed.	To enhance postural control, reduce pain, and improve function.
Bracing	Custom thoracolumbar braces like Rigo-Chêneau brace or soft lumbar supports.	Provides spinal support, improves balance, and slows curve progression.
Pharmacological therapy	Long-term NSAIDs (e.g., naproxen) or acetaminophen for pain relief. Adjuncts like muscle relaxants and neuropathic pain medications may be included.	Reduces inflammation, relieves pain, and manages symptoms without addressing deformity.
Epidural steroid injections	Localized injections of corticosteroids combined with anesthetics.	Targets inflammation and pain in cases of spinal stenosis or radiculopathy, offering short-term relief.
Weight management	Weight loss programs for overweight individuals or nutritional plans for those underweight.	Minimizes axial loading, reducing mechanical stress on the spine.
Lifestyle modifications	Daily low-impact exercises (e.g., swimming, cycling) and ergonomic adjustments for daily activities.	Maintains mobility, reduces stress on the spine, and improves overall physical well-being.
Psychological support	Cognitive behavioral therapy (CBT) or mental health counseling.	Addresses depression, anxiety, or self-image issues associated with scoliosis.
Assistive devices	Use of walkers, rollators, or canes.	Enhances mobility, alleviates pain during movement, and reduces fall risks.
Alternative therapies	Acupuncture, yoga, or Pilates tailored for scoliosis.	Promotes relaxation, pain relief, and improved flexibility.
Nutritional supplements	Calcium and vitamin D supplementation to improve bone health, especially in osteopenia or osteoporosis.	Reduces risk of fractures and supports skeletal health.

pelvis, inclusive of the iliac crests.^[40] To accurately measure spinal balance and curvature on PA and lateral radiographs, it is essential that the patient is positioned in a standing posture with knees extended, hips relaxed, and fingertips placed on the clavicles.^[28,41] The standing position is necessary because lying down eliminates the effect of gravity, reduces the magnitude of curvature, and limits the ability to assess coronal and sagittal balance.^[42,43] The Cobb angle is the standard measurement of scoliosis severity, with higher angles indicating more severe cases. The evaluation of trunk shift is done by the overhang of the rib cage relative to the iliac crest. Lateral listhesis, often at L3-L4, is measured in millimeters of vertebral overhang and linked to curve progression.^[2]

One of the more fundamental metrics for understanding the extent of spinal deformities is the Cobb angle; however, the information achieved through this metric offers incomplete information regarding scoliosis. This is caused by the Cobb angle not being able to address sagittal alignment, which is one of the most significant components for comprehending quality and functionality of life.^[44] A complementary assessment called sagittal balance provides crucial information regarding overall spinal alignment. One of the pivotal parameters in this regard is SVA. The SVA is defined as the horizontal distance from the C7 plumb line to the S1 sacral endplate and has been proven to have significant relations with clinical outcomes.^[41] Building upon this framework, Duval-Beaupère et al.^[42] identified three spinopelvic parameters (PI, PT, and SS) that significantly influence sagittal alignment. Pelvic incidence, an anatomical constant, represents the angle between a line perpendicular to the sacral endplate and a line connecting the sacral midpoint to the hip axis. It serves as a determinant of lumbar lordosis and sagittal balance.^[45] Pelvic tilt, a dynamic parameter, reflects pelvic rotation in the sagittal plane and compensates for sagittal imbalance, with high values indicating pelvic retroversion. Finally, SS, defined as the angle between the horizontal axis and the sacral endplate, is directly proportional to PI and is critical for maintaining lumbar lordosis (Figure 1). Collectively, these parameters offer a comprehensive understanding of spinopelvic alignment in adult scoliosis, aiding in both surgical planning and outcome assessment.^[45-47]

One of the more common and more frequently used diagnostic tools for ADS patients who have

presentations of radicular pain (often resulting from neural foraminal or far lateral root compression, or neurogenic claudication, which may arise from central, foraminal, or subarticular spinal stenosis) is magnetic resonance imaging.^[41,44]

Computed tomography is imperative for meticulous evaluation of bony structures, encompassing fractures, osteophytes, and spondylolisthesis, in addition to assessing the integrity of surgical constructs. Furthermore, the employment of advanced techniques, such as vertical spine reconstructions, facilitates a comprehensive understanding of spinal alignment, thereby enhancing diagnostic accuracy and surgical planning.^[41,44]

Conservative Therapies

The data presented in Table 4 offer a comprehensive overview of the diversity and impact of the methodologies employed in the conservative management of ADS. The conservative management of ADS is focused on alleviating symptoms, enhancing functionality, and postponing or circumventing surgical intervention, particularly in cases of mild to moderate deformities or substantial comorbidities. This approach aims to preserve functionality in patients deemed unsuitable for surgical procedures. A limited number of randomized trials have been conducted on conservative treatments for adult scoliosis, and these studies have demonstrated some degree of efficacy for the interventions.^[48-50] Bracing constitutes a pivotal component of conservative management for ADS, particularly in cases of mild to moderate deformities or when patients are deemed unsuitable candidates for surgical intervention. The primary objectives of bracing are to stabilize the spine, mitigate pain, and enhance functional capacity. In contrast to surgical interventions targeting structural corrections, bracing aims to alleviate symptoms through optimization of spinal alignment and reduction of mechanical stress on affected vertebral segments. This therapeutic modality serves to alleviate discomfort and improve patients' ability to perform daily activities, contributing to an overall better quality of life.^[51]

Surgical therapies

Surgical intervention for adult scoliosis is generally considered a last resort for patients with substantial deformities, progressive curvatures, or severe pain and neurological symptoms that do

TABLE 5
A comprehensive overview of surgical techniques for adult scoliosis with reference

Surgical technique	Description	Indications	Advantages	Limitations
Posterior spinal fusion (PSF)	Corrects deformities using posteriorly placed rods and screws to achieve alignment and fusion.	Flexible curves, coronal and sagittal imbalance, degenerative changes.	Widely applicable, provides robust fixation and correction.	Higher surgical morbidity in older patients.
Anterior spinal fusion (ASF)	Achieves spinal fusion through an anterior approach, often in conjunction with interbody cages.	Selected cases requiring anterior column support, primarily thoracolumbar deformities.	Restores anterior column support, improves fusion rates.	Limited application for complex deformities or posterior issues.
Lateral lumbar interbody fusion (LLIF)	Accesses the spine laterally, placing interbody cages to restore disc height and alignment.	Moderate deformities, disc height restoration, indirect decompression of stenosis.	Minimally invasive approach, indirect decompression, improved disc height.	Risk of psoas muscle and lumbar plexus injury.
Transforaminal lumbar interbody fusion (TLIF)	Combines posterior instrumentation with interbody cage placement through a posterior approach.	Local kyphosis, sagittal imbalance, single-level instability.	Direct decompression, effective sagittal alignment correction.	Technically demanding, potential nerve root injury.
Minimally invasive surgery (MIS)	Focuses on smaller incisions, reducing soft tissue disruption and recovery time.	Mild to moderate deformities, patients with significant medical comorbidities.	Reduced blood loss, quicker recovery, less postoperative pain.	Limited corrective power for severe deformities.
Osteotomies	Resections or modifications of bone structures (e.g., pedicle subtraction osteotomy) to improve alignment.	Fixed deformities, significant sagittal imbalance, prior failed fusion.	Provides significant correction for fixed deformities.	Requires significant surgical expertise, increased operative time and blood loss.
Vertebral column resection (VCR)	Involves removal of a vertebral segment to correct severe deformities.	Severe rigid deformities, sharp kyphosis, or scoliosis with significant neurologic compromise.	Addresses the most severe deformities with maximal correction.	High surgical risk, prolonged recovery.

not respond to conservative treatment methods (Table 5). The primary objectives of surgical intervention include the correction of spinal alignment, the relief of nerve compression, the improvement of sagittal and coronal balance, and the enhancement of the patient's overall quality of life and functional abilities.^[52-55]

In conclusion, the management of adult scoliosis necessitates a comprehensive and evolving approach that integrates diagnostic, therapeutic, and rehabilitative strategies. While conservative management continues to play a pivotal role in the management of symptoms for mild to moderate deformities, there is a pressing need for more randomized controlled trials to evaluate the efficacy

of physical therapy, bracing, and pharmacological interventions. Surgical intervention remains the prevailing standard for severe cases, with ongoing advancements in techniques aimed at enhancing safety, reducing complications, and achieving optimal balance restoration. However, the indications for surgery, particularly in the aging population, require further clarification. Future research should prioritize the development and application of minimally invasive technologies, enhanced preoperative planning, and long-term functional outcomes to personalize care. A multidisciplinary approach, incorporating clinical expertise, patient-centered decision-making, and ongoing innovation, is essential to meet the complex challenges of managing adult scoliosis effectively.

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